Pollution as an evolutionary trigger in peppered moths

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Abstract. The impact of humans on the life of other animals and living beings can be fairly different from all the other means of influence. For instance, pollution could be an anomalous trigger. In this paper, we investigate through a computational model the way pollution impacted the evolution of Biston betularia (peppered moths).

Keywords: Agent-based · Modelling · Evolution · Adaptation · pollution · moths

1 Introduction

"Biston betularia" also known as "peppered moth" derives the latter name by its black spots on its wings and body (4). This moth is spread throughout Asia, Europe, and even North America. However, only a specific subset of their population exhibited a phenomenon that this paper aims to investigate: the moths over the territory of the united kingdom. As it is widely described by Cook and Saccheri (2), during the first industrial revolution these moths saw a significant increase in their level of melanin, which resulted in a major blackening of their wings and body. According to those authors, evidence strongly points to pollution as a trigger for this change. Mostly-white moths were camouflaging on light lichens on top of tree bark in order to increase their chance of survival. However, air pollution killed most of these lichens, significantly decreasing the fitness of that trait. This way, only the dark bark underneath was the only mean of camouflage for moths. Therefore, new generations of moths started becoming darker to better adapt to this new environment.

The aim of this paper is to provide a model of this phenomenon. In order for a theory to be validated, it is of acute importance that its predictions are correct and applicable. Since replicating such a phenomenon in the real world would be extremely invasive, difficult, and unethical, a computational model has been created.

2 Research question and hypotheses

The following is the research question that it is going to be investigated:

Does a higher level of pollution lead to a change in genotype of peppered moths leading to increasingly blacker body and wings?

This research question allows us to formulate the following hypotheses:

H_0*: A higher level of air pollution does not lead to a change in the genotype of the moths regarding "blackness".*

H_1*: A higher level of air pollution leads to a change in the genotype of the moths increasing their "blackness".*

From the aforementioned hypotheses, we can derive that a right-tailed test is going to be needed, namely measuring whether blackness increases along with pollution (H_1) or not (H_0).

3 Model

The framework that has been used for this model is *"Netlogo"*, an agent-based programming language and environment. Netlogo is extremely useful for its simplicity combined with a number of features that simplified the process of modeling, testing and experimenting. Agent-based modeling is a paradigm that allows to model the behavior of a single individual in a collective environment, allowing to observe and investigate emerging phenomena (1). Its usefulness comes from the intuitiveness of modeling the behavior of a single individual rather than discovering a universal mathematical formula that governs a phenomenon.

An arbitrary number of 300 moths are created at the beginning of the simulation. The reason why an arbitrary number has been chosen is that the population is expected to vary largely and its size is not of large interest to our simulation. All the moths are created at a random position in the "map" facing a random direction. Moreover, each moth is given a random "blackness" between 5% and 15%. This blackness represents the number and thickness of the black spots on the body and wings of the moths, and the margin has been implemented to allow variance and thus promote evolution. In addition, a random gender has been assigned to each moth in order for them to reproduce. Furthermore, the actions that a moth can perform are: *moving*, *reproducing*, and *dying*. Finally, moths with blackness above 50% will be displayed as black (see Fig. 1). This feature is purely aesthetic, but it might help visualize the effectiveness of the model.

Moths move so that they can find a partner to breed, but it has been decided not to complicate this action further, as it is not relevant to answer the research question. There is no evidence to assume that a particular path to breeding would influence the emergence of our wanted phenomenon.

When a female moth is near a male moth, they can start reproducing. The blackness of the child will be the mean of the blackness of the parents with a variation of 5%. This way, it is not only possible to ensure that the child will inherit the traits of its parents, but also that there is going to be a margin for natural selection to happen. It has been established that only one child will be released after the reproduction. In the real world, moths will lay several eggs, and many are going to survive (5). However, in this model, only one child will

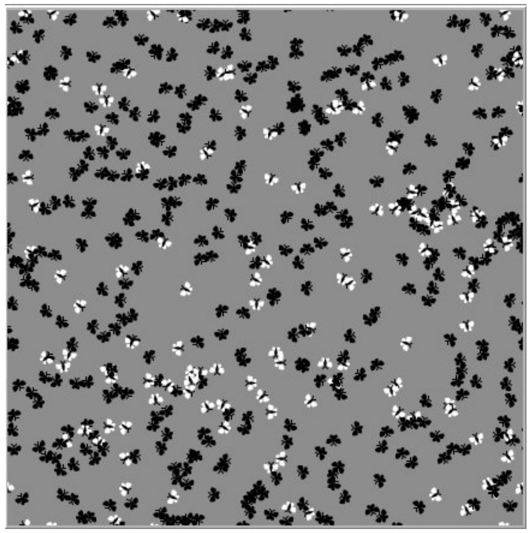

Fig. 1. A population of moths that has mostly turned black. such a visualization can help the researcher assess that the model is behaving as expected.

be born. The reason for this choice is that "laying several eggs" would have no practical advantage in our model. Indeed, it would easily cause overcrowding and it would not help genetic variation, which is what we want to encourage the most in our model. This choice does not seem to have an impact on the representativeness of the model either. Indeed, the number of children would only impact the time needed for the spread of a certain gene, and time is not a value that we are interested in on an absolute level. Nonetheless, we might be interested in knowing that one simulation reaches a result more quickly than another, but that is not impacted by such choices. In conclusion, the gender and the position of the newborn moth will be chosen randomly.

Each turn each moth has a chance of dying. There are two dying conditions: old age and being hunted. Old age has been implemented as a form of crowd control. It was not possible to creates a stable population for a long period of time using only being hunt as a condition. The reason for that is that it would simply be unrealistic. In the real world, the population is controlled through unexpected events such as lack of resources, climate change, and catastrophes such as earthquakes, volcano eruptions, and droughts (3). Since these phenomena are unrealistic to model and would also be out of scope, only a very strict "old age" death has been created. After 8 turns of living, any moth is going to die unless the population is below 500. Without this last condition, the whole population will quickly die out. Let us now consider the very core of the model: the death caused by being hunted. the probability of dying is formulated as follows:

$$whiteness^{\frac{pollution}{2}} - 0.53$$

First of all, pollution and blackness are divided by 100 so that the value will always be between 0 and 1. whiteness is the negation of blackness. the "power" has been chosen as the main operator so that the base can significantly increase the probability while the increasing exponent will dull the impact of the base for lower values of the latter. The exponent is divided by 2 so that $pollution > .5$ won't start decreasing the probability for higher values of whiteness. In other words, as the pollution keeps increasing the probability of death increases accordingly as the whiteness also rises. A constant is finally subtracted to avoid extreme shifts in probability.

4 Experiment

The user, along with the "setup", "go", and "tick" (go for one tick) buttons is given the possibility to manipulate the level of pollution of the simulation through a slider. In the meantime, it is possible to see a monitor with the current average blackness, a plot with the variation of blackness over time, and a plot with the population over time (see Fig. 2). These outputs are useful for preliminary tests about the total population (overcrowding and quick extinction) and the number of ticks needed to show coherent and relevant results. The former has been discussed in the previous section, the latter has been established to be a time of 600 ticks. This number has been chosen so that the simulation can show consistent results without neither being stuck to a floor where moths do not have enough time to evolve nor reaching a ceiling where higher values of pollution would steadily correlate to the maximum range of values for average blackness.

The simulations have been performed using the *"BehaviorSpace"* tool in Netlogo (see Fig. 3). This tool has been set to run for every two values of pollution from 0% to 90% four times. In essence, the tool has run four simulations for 0% pollution, four simulations for 2% pollution, and so on. This results in a total of 184 simulations.

The values that have been tracked for each simulation are the pollution and the final average blackness. if the final average blackness consistently increases as higher values of pollution are set, our null hypothesis is rejected and our research question answered.

5 Results

The data has been gathered in a CSV file thanks to BehaviorSpace. The CSV file can be organized in a table as it is possible to see below (see Fig. 4). the data-set has then been analyzed and validated using *"RStudio"*. It is possible to see how a scatter-plot with the pollution on the X-axis and the average blackness on the Y-axis has been created (see Fig. 5).

From the plot, it is possible to derive that there seems to be a linear positive correlation between pollution and final average blackness. If the statistical tests validate this correlation, then the null hypothesis can successfully be rejected.

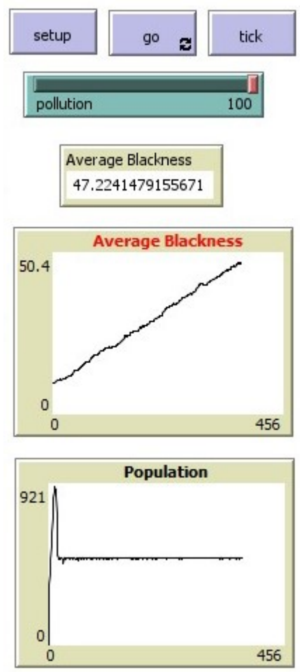

Fig. 2. The inputs (blue) and outputs (beige) of the model.

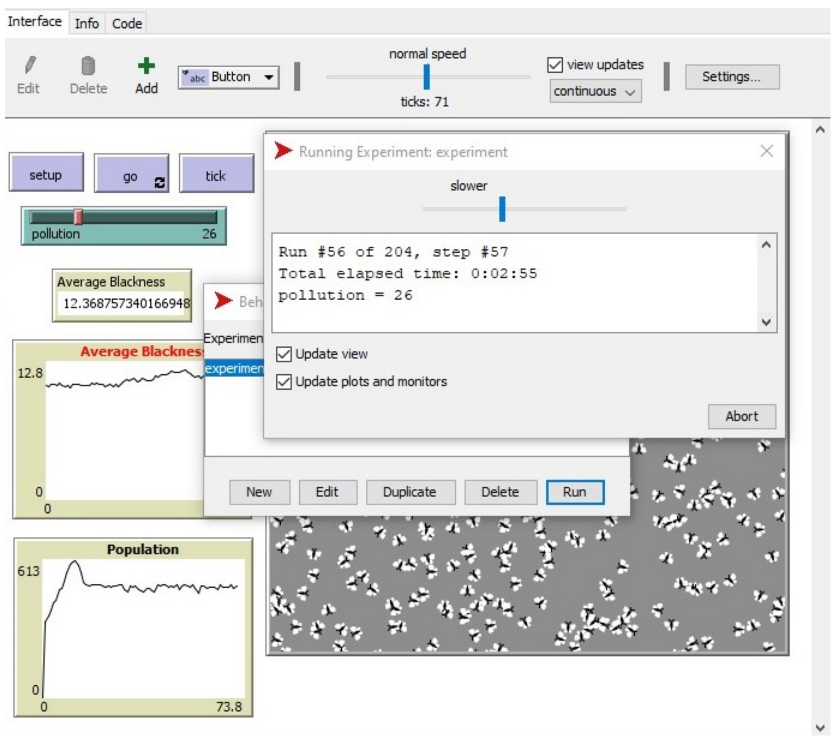

Fig. 3. The BehaviorSpace tool in Netlogo

Run number	Pollution	Average Blackness	Run number	Pollution	Average Blackness	Run number	Pollution	Average Blackness	Run number	Pollution	Average Blackness
4	0	15,8063	47	22	27,4541	93	46	48,6781	139	68	72,8333
2	0	13,6076	48	22	24,2542	95	46	49,6004	141	70	68,9036
3	0	10,4355	49	24	23,1192	94	46	59,3847	140	68	63,4531
1	0	8,7212	50	24	21,5993	96	46	47,1789	142	70	67,2554
5	2	15,7058	51	24	37,2423	97	48	49,5604	144	70	72,4683
6	2	10,6833	52	24	28,4339	98	48	40,6579	143	70	66,3925
7	2	12,6759	53	26	26,8408	99	48	36,7570	145	72	61,9460
8	2	12,7997	54	26	32,6271	100	48	59,4898	146	72	68,9684
9	4	13,0001	55	26	29,5134	101	50	54,2026	147	72	71,5736
10	4	14,5572	56	26	33,3251	102	50	50,4804	149	74	63,8299
11	4	8,8694	57	28	28,6995	103	50	58,4068	148	72	63,8778
12	4	9,6302	58	28	37,0899	104	50	48,3712	150	74	73,3890
13	6	17,2388	59	28	21,2000	105	52	57,9994	151	74	69,5778
14	6	18,1839	60	28	35,3536	106	52	48,3015	152	74	68,3059
15	6	10,3665	61	30	41,3242	107	52	59,4148	153	76	72,8744
16	6	18,9527	62	30	30,8895	108	52	56,9886	154	76	71,2882
17	8	24,1001	63	30	34,5258	109	54	50,0541	155	76	75,3185
18	8	20,0969	64	30	41,0227	110	54	50,9713	156	76	69,7055
19	8	20,9333	65	32	32,3997	111	54	35,0173	157	78	72,2915
20	8	18,7544	66	32	38,6754	112	54	58,5456	158	78	75,4647
21	10	20,7353	67	32	34,7518	113	56	62,9541	159	78	75,7183
22	10	20,8930	68	32	35,4638	114	56	59,6976	160	78	78,2810
23	10	25,7742	69	34	35,9364	115	56	56,7352	161	80	76,4346
24	10	18,0614	70	34	35,7153	116	56	48,6504	162	80	65,1102
25	12	23,3027	71	34	31,7558	117	58	67,2297	163	80	69,5963
26	12	21,8135	73	36	43,0281	118	58	47,7246	164	80	60,7406
27	12	13,1528	72	34	35,7395	119	58	55,9580	165	82	78,7450
28	12	24,8028	74	36	34,6632	120	58	56,1223	166	82	72,5893
29	14	22,7900	75	36	45,6137	121	60	60,2404	167	82	76,9990
30	14	20,5232	76	36	32,6750	122	60	45,2198	168	82	72,7219
31	14	19,5602	77	38	28,3122	123	60	54,9942	169	84	72,7227
32	14	20,2676	78	38	48,0249	124	60	63,2152	170	84	76,6854
33	16	14,8836	79	38	50,3788	125	62	59,0078	171	84	74,9408
34	16	17,5275	80	38	42,6059	126	62	54,4948	172	84	75,5175
35	16	25,2277	81	40	47,3248	127	62	59,5146	173	86	75,1516
36	16	15,8408	82	40	56,4355	128	62	58,9322	174	86	76,4954
37	18	31,5058	83	40	30,7459	129	64	59,5079	175	86	77,7351
38	18	27,7943	84	40	34,6255	130	64	69,1473	176	86	77,0549
39	18	30,1050	85	42	53,3903	131	64	63,4600	177	88	76,0877
40	18	13,4829	86	42	39,9753	132	64	69,0995	178	88	72,9193
41	20	32,8146	87	42	42,6902	133	66	67,2804	179	88	77,2573
42	20	27,9320	88	42	40,1730	134	66	65,0657	180	88	76,5446
43	20	17,2204	90	44	36,7662	135	66	60,9738	181	90	73,8735
44	20	28,6521	89	44	46,2665	136	66	70,8781	182	90	75,0046
45	22	25,5153	91	44	48,1658	137	68	75,9963	183	90	75,3578
46	22	26,4649	92	44	42,2542	138	68	52,3100	184	90	76,1149

Fig. 4. All the data collected through BehaviorSpace in NetLogo.

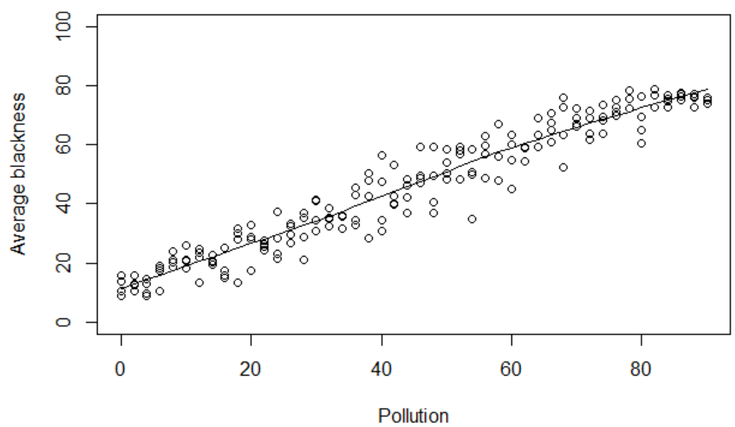

Fig. 5. This scatter-plot shows the correlation between the average blackness and level of pollution.

6 Discussion

6.1 Statistical analysis

As it has been illustrated in the previous section, a **correlation** between **two** continuous variables has to be validated. Thus, the correct test needed for the validation of this kind of claim is a correlation test. However, whether the data is normally distributed needs to be checked before choosing the type of correlation test. In order to do that, we need to perform a *Shapiro-Wilk test* on both the pollution levels and the average blackness. we will use a value of $\alpha = .05\%$.

Pollution: p-value = 9.627e-06

Average blackness: p-value = 2.768e-07

Since both p-values are (significantly) lower than α, we can reject the null hypothesis that the data distribution is similar to a normal distribution. With this premise, a *Spearman* or *kendall*'s test has to be performed. For this study, a *Spearman's test* has been chosen. $\alpha = .05\%$ has been established again. The test has given the following results:

$\rho = 0.9670305$

p-value < 2.2e-16

Since ρ is extremely high, and the p-value is significantly lower than α, we can reject our null hypothesis that there is no correlation between pollution and final average blackness, I.E. a higher level of pollution leads to a change in the genotype of the moths, increasing their blackness.

6.2 Relevance

Although the model confirmed the initial assumption, the limitations of the model have to be addressed. In particular, the reproduction of the moths in the model is substantially different from the real mean of reproduction in real moths. These differences have been discussed in the "model" section and have been justified with the lack of evidence of their impact on this factor of evolution. Further research should be pursued in order to confirm or falsify this assumption.

7 Conclusion

In this paper the phenomenon of Biston betularia progressive becoming blacker as a mean of adaptation to air pollution has been described. Furthermore, a model has been developed to validate the claim that there is indeed a correlation between pollution and the "blackness" of the moths. The model succeeded in proving this correlation and an appropriate statistical analysis confirmed the consistency of our measurements.

The limitation of modelling a mean of reproduction that was not equivalent to the real one was discussed, and investigating the impact of such a choice through following studies has been proposed to further solidify the evidences collected during this research. Reusing this or a model with a similar goal and confronting the results collected using different means of reproduction would be a viable option to investigate the impact of this choice.

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